Computational Evaluation of Polyethylene-Reflected Plutonium Metal Neutron Multiplicity Measurements

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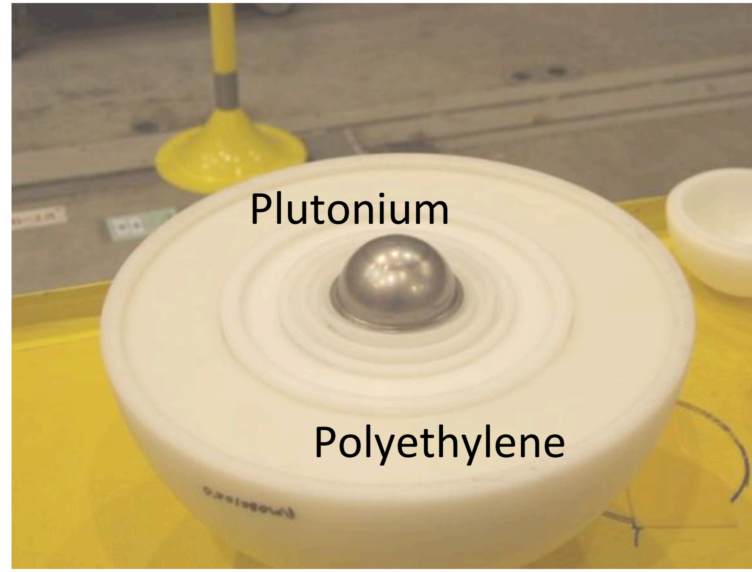
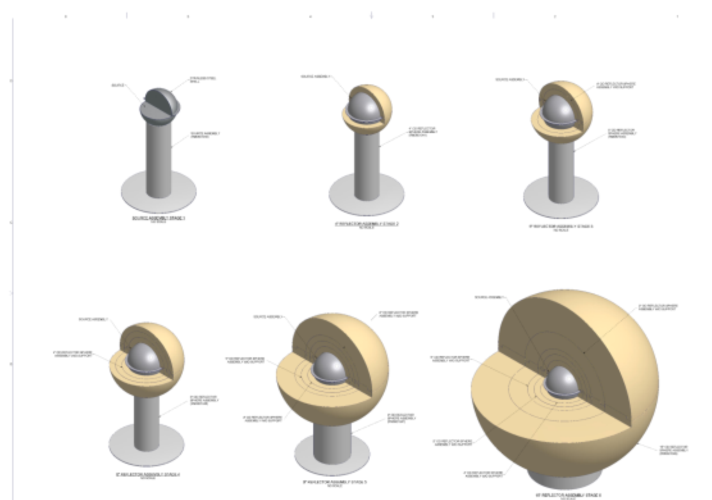
Introduction

- In 2009, NCSP co-sponsored a series of benchmark experiments with polyethylene-reflected plutonium metal
- The experiments were conducted by Sandia and LANL at Nevada Test Site
- We performed simultaneous neutron multiplicity and gamma spectrometry measurements of the BeRP ball reflected by 0 – 6” of polyethylene
- The primary objective was to acquire benchmark measurements to validate a new inverse transport solver in GADRAS, which simultaneously analyzes gamma spectrometry and neutron multiplicity measurements
- Another objective was to publish the measurements to validate neutron multiplicity calculations by other codes, e.g., MCNPX-PoliMi

Polyethylene-Reflected Plutonium Metal

- Source: BeRP ball
  - Plutonium metal sphere
  - 4438 g Pu
  - 19.6 g/cm^3 (alpha phase)
  - 94% Pu-239
- Reflectors
  - Nesting polyethylene spherical shells
  - 0.95 – 0.96 g/cm^3 (HDPE)
  - Total thickness: 0.5 – 6.0 in
- 6 different configurations were measured

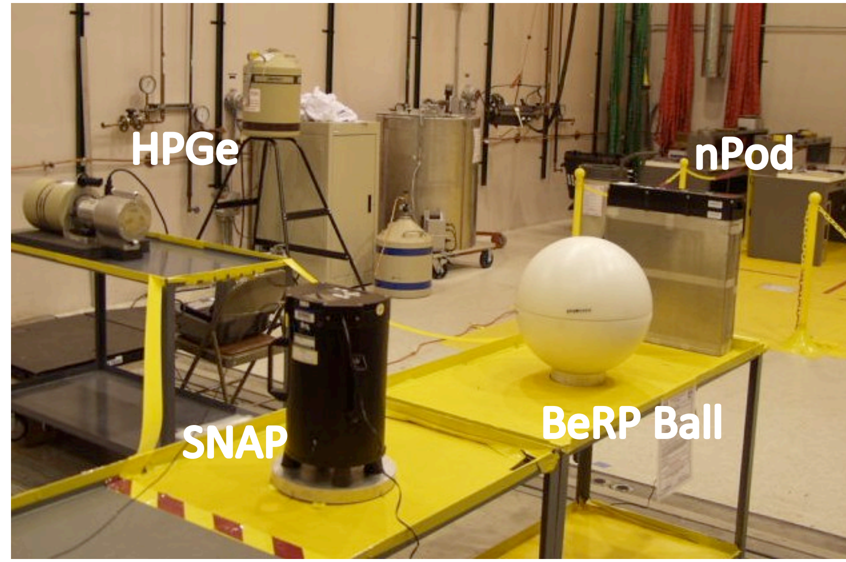


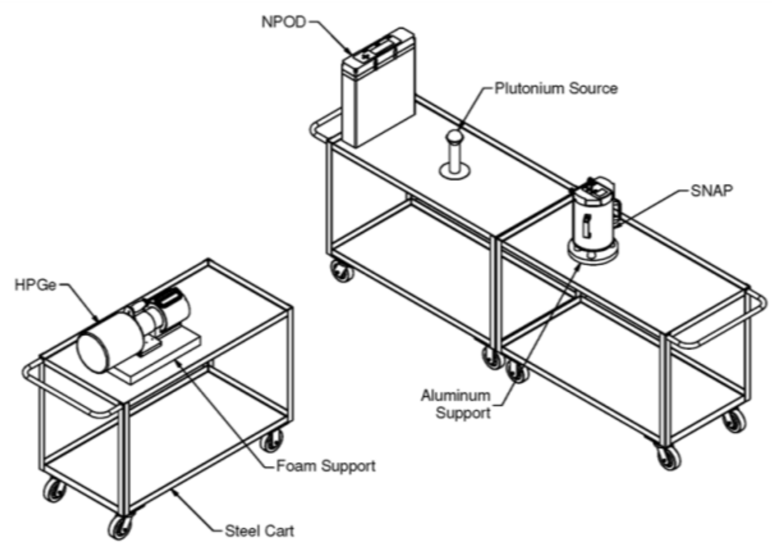


Reflector Configurations

Experiment Setup

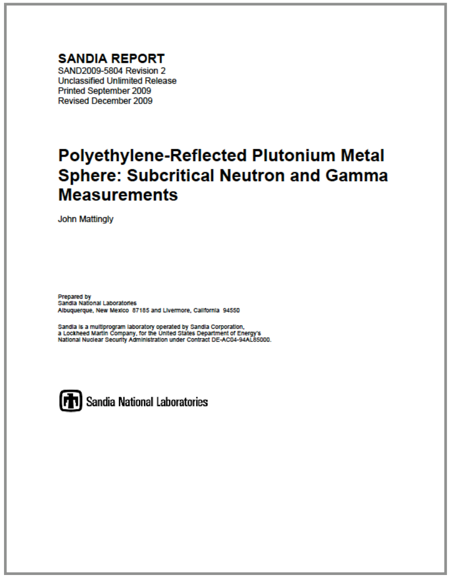
- Neutron multiplicity counter: nPod
  - 15 × 10-atm He-3 counters
  - HDPE moderator block wrapped in Cd
  - 0.5 m from source
- Gross neutron counter: SNAP
  - 1 × 10-atm He-3 counter
  - Layered HDPE/Cd moderator
  - 1.0 m from source
- Gamma spectrometer: HPGe
  - 150% relative efficiency
  - 1-in-thick Bi radial shield
  - 2.0 m from source





Experiment Results

- The benchmark experiments helped us identify and fix some problems with the GADRAS multivariate inverse transport solver
- The solver correctly estimated plutonium mass and neutron multiplication within 10% in all 6 cases
- The solver was used in 2009 at the Fall Classic exercise, which helped us identify and fix a few other problems
- The benchmark data were published with a detailed report in SINBAD2010 now available from RSICC
- The experimental validation of the solver was published in an invited paper at SORMA in 2010 and in NIM early this year



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Polyethylene-Reflected Plutonium Metal Sphere: Subcritical Neutron and Gamma Measurements

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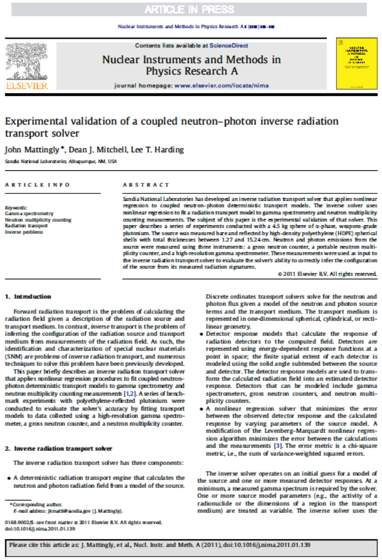

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Experimental validation of a coupled neutron–photon inverse radiation transport solver

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ARTICLE INFO

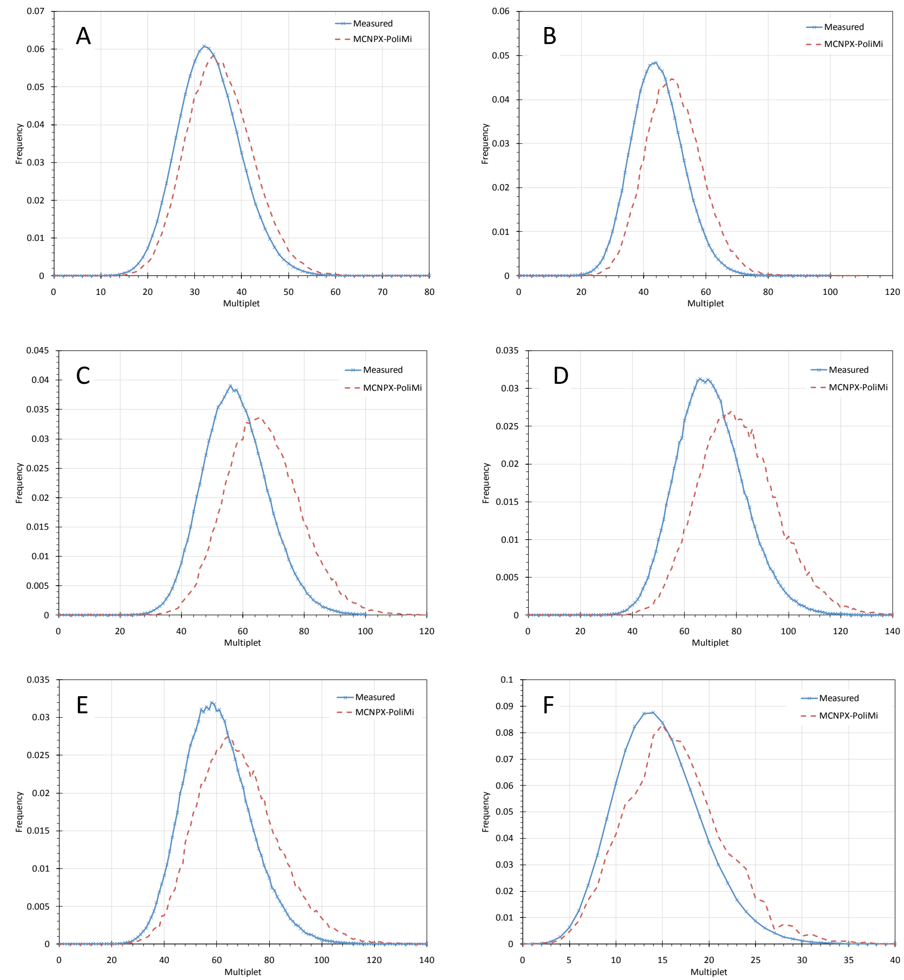
ABSTRACT

1. Introduction

2. Inverse radiation transport solver

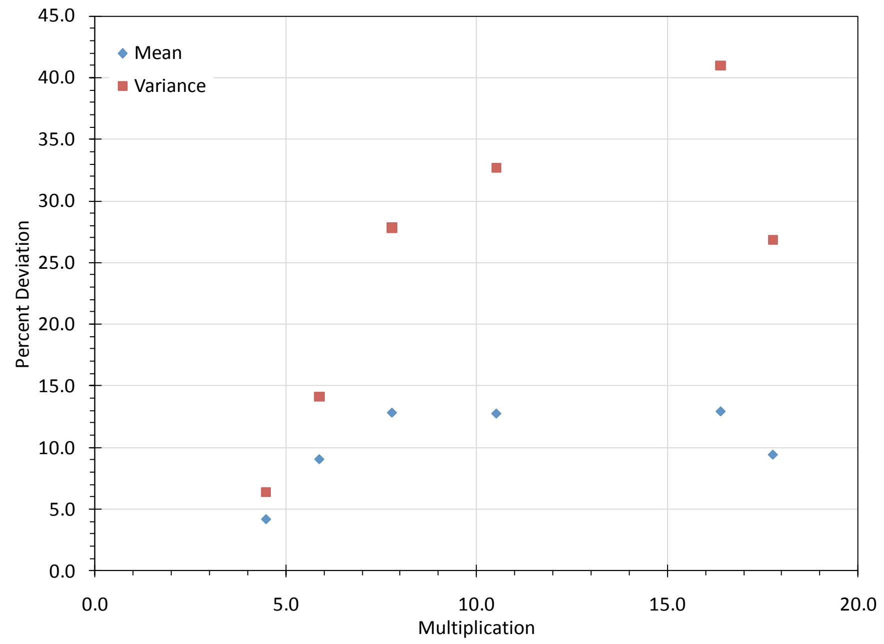
MCNPX-PoliMi Simulations

- The benchmark measurements were also used to test MCNPX-PoliMi
- Systematic errors in the calculations were observed
- The calculations consistently over-predicted the mean and variance of the multiplicity distribution
- The magnitude of the error tended to increase with increasing multiplication



Errors in the Calculated Multiplicity Distributions

Reflector	Multiplication	Deviation from Experiment	
		Mean	Variance
None	4.5	4.2%	6.4%
0.5"	5.9	9.0%	14.1%
1.0"	7.8	12.8%	27.8%
1.5"	10.5	12.8%	32.7%
3.0"	16.4	12.9%	41.0%
6.0"	17.8	9.4%	26.8%



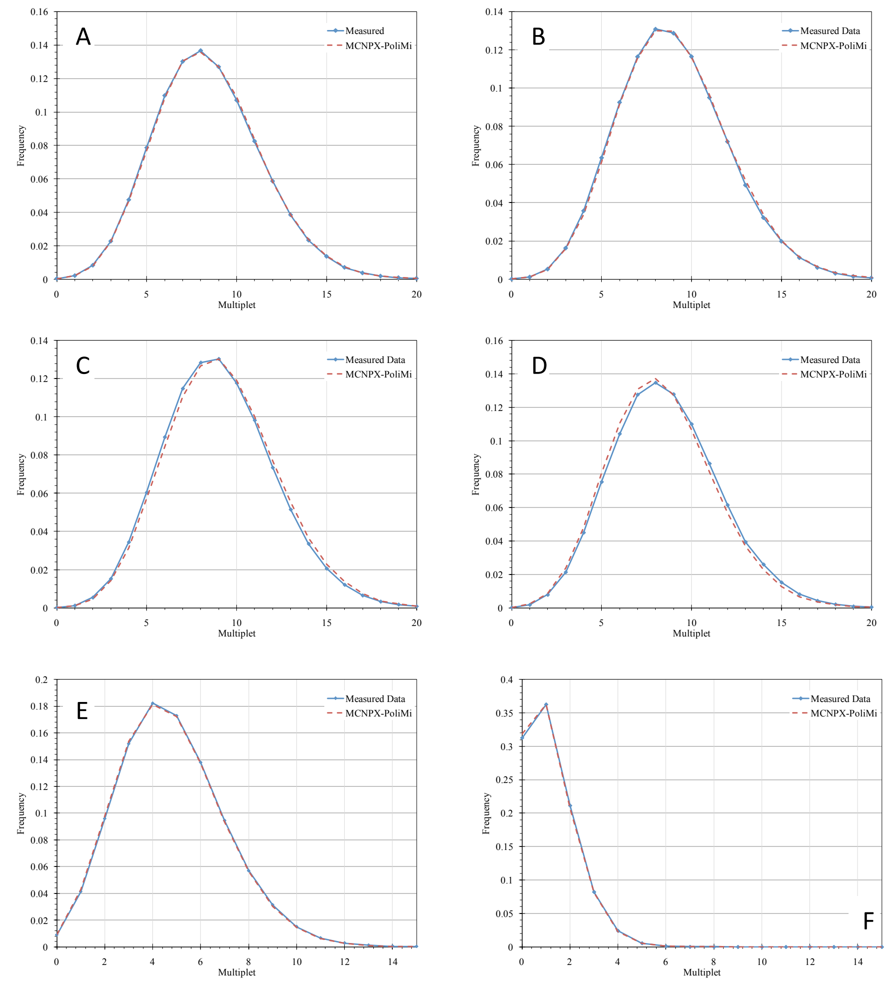
Mean and variance refer to the centroid and width of the multiplicity distribution

Potential Causes of Errors

- Geometry/material errors in the nPod model
- Geometry/material errors in the polyethylene reflector models
- Inadequate correction for nPod dead-time
- Geometry/material errors in the BeRP ball model
- Errors in the nuclear data for plutonium

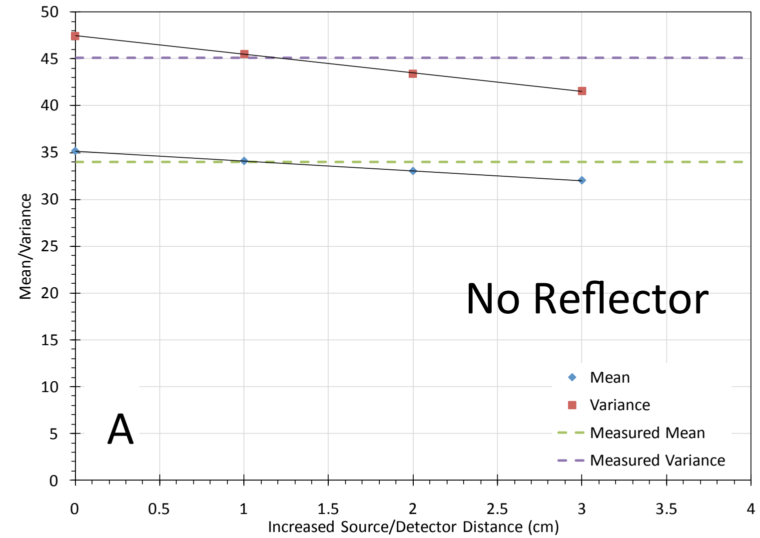
MCNPX-PoliMi Simulations of Reflected Cf-252

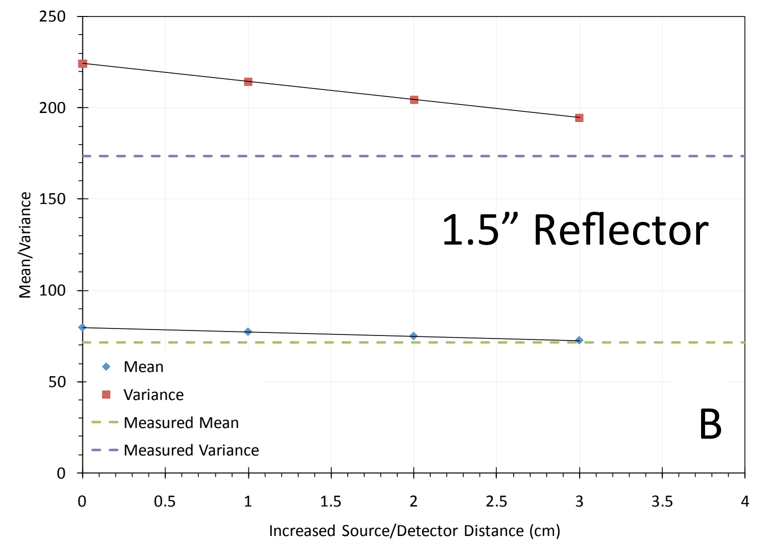
- Measurements were also performed using a Cf-252 source inside each reflector
- MCNPX-PoliMi correctly predicted the multiplicity distribution in all 6 cases
- This test validated the geometry and material models of the poly reflectors and the nPod
- Note the neutron multiplication is 1 in each case



Source-Detector Distance

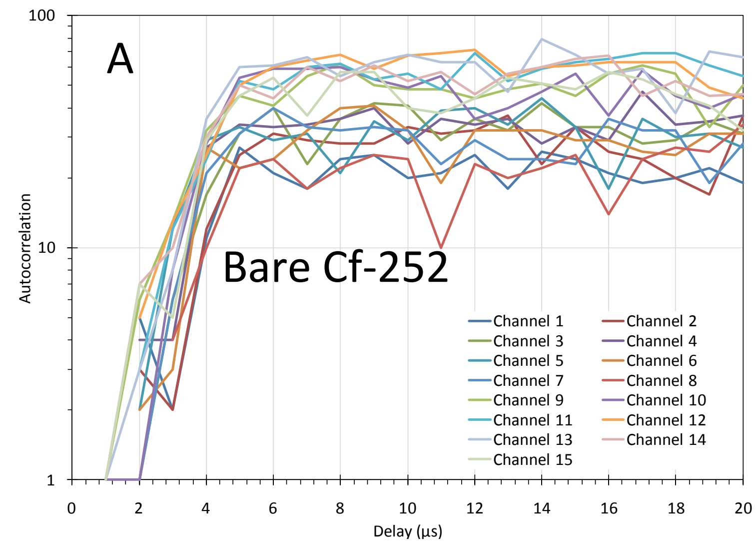
- The distance between the BeRP ball and the nPod was carefully controlled and repeatedly measured
- The uncertainty in the source-detector distance was less than 0.5 inch
- No consistent, plausible error in the source-detector distance corrected all of the calculations

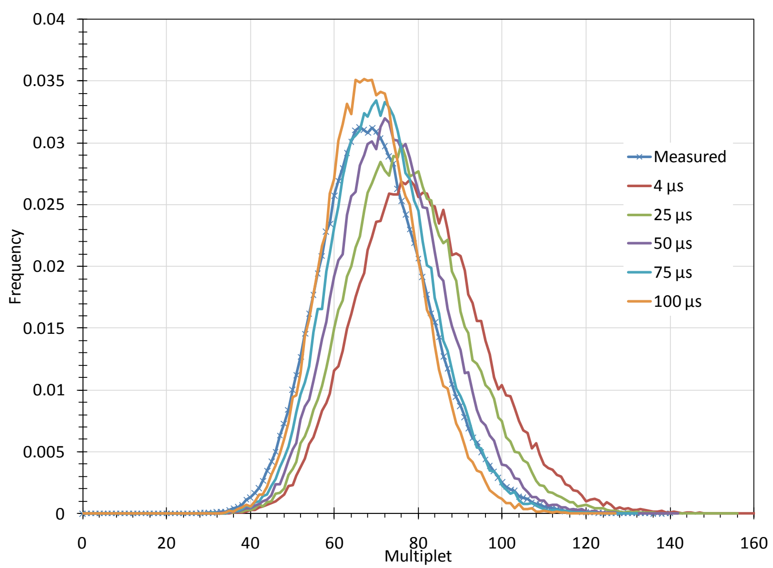


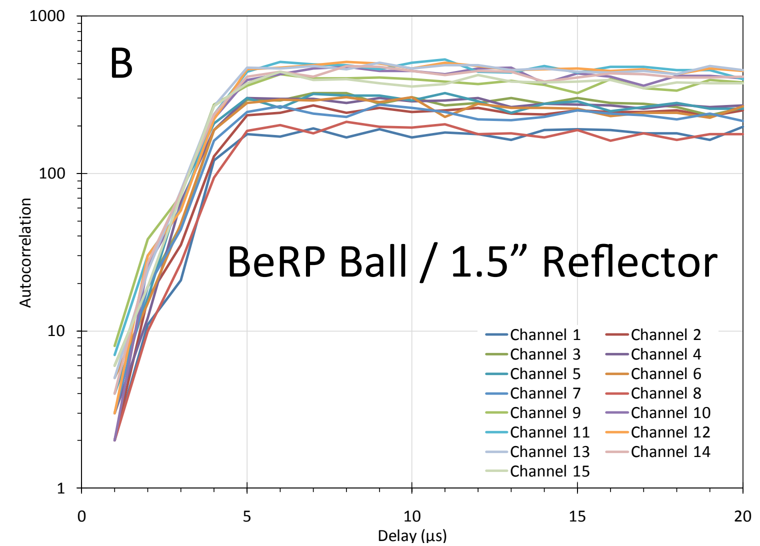


Detector Dead-Time

- The dead-time of each He-3 counter in the nPod was measured
- Each counter had a dead-time of about 2.5 μs
- The dead-time required to correct the MCNPX-PoliMi calculations was nearly 100 μs

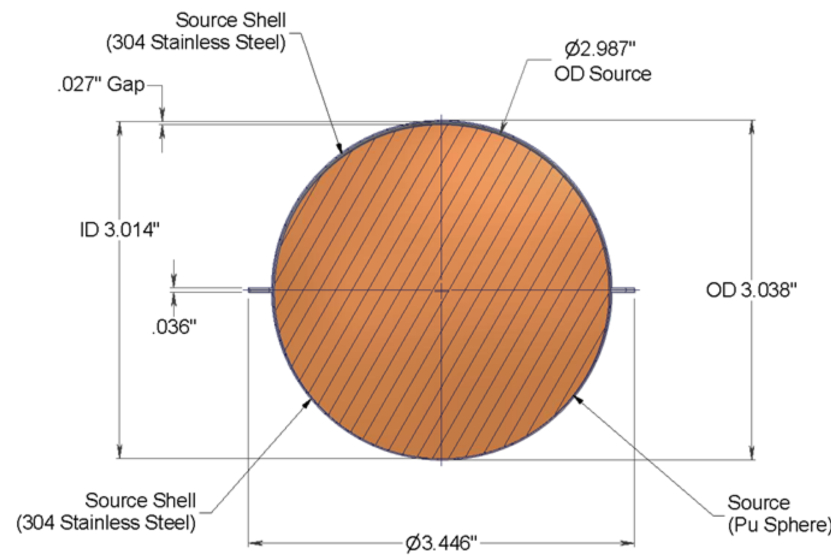






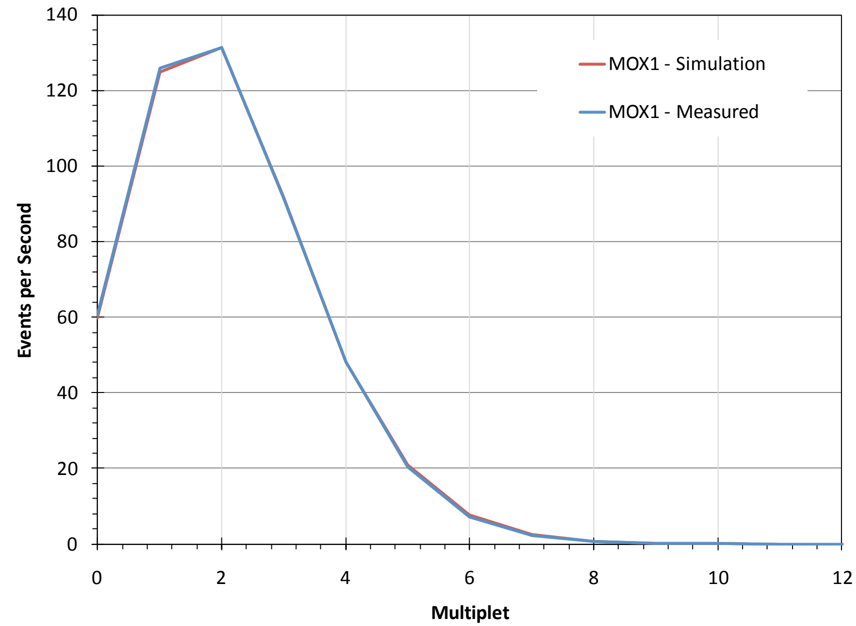
Plutonium Density

- The BeRP ball plutonium mass is known within 1 g
- However, the interior of the steel cladding permits radial expansion up to 0.027"
- The expansion is definitely less than the maximum, because you can feel the plutonium rolling around in the cladding
- No plausible change in the plutonium density corrected the MCNPX-PoliMi calculations

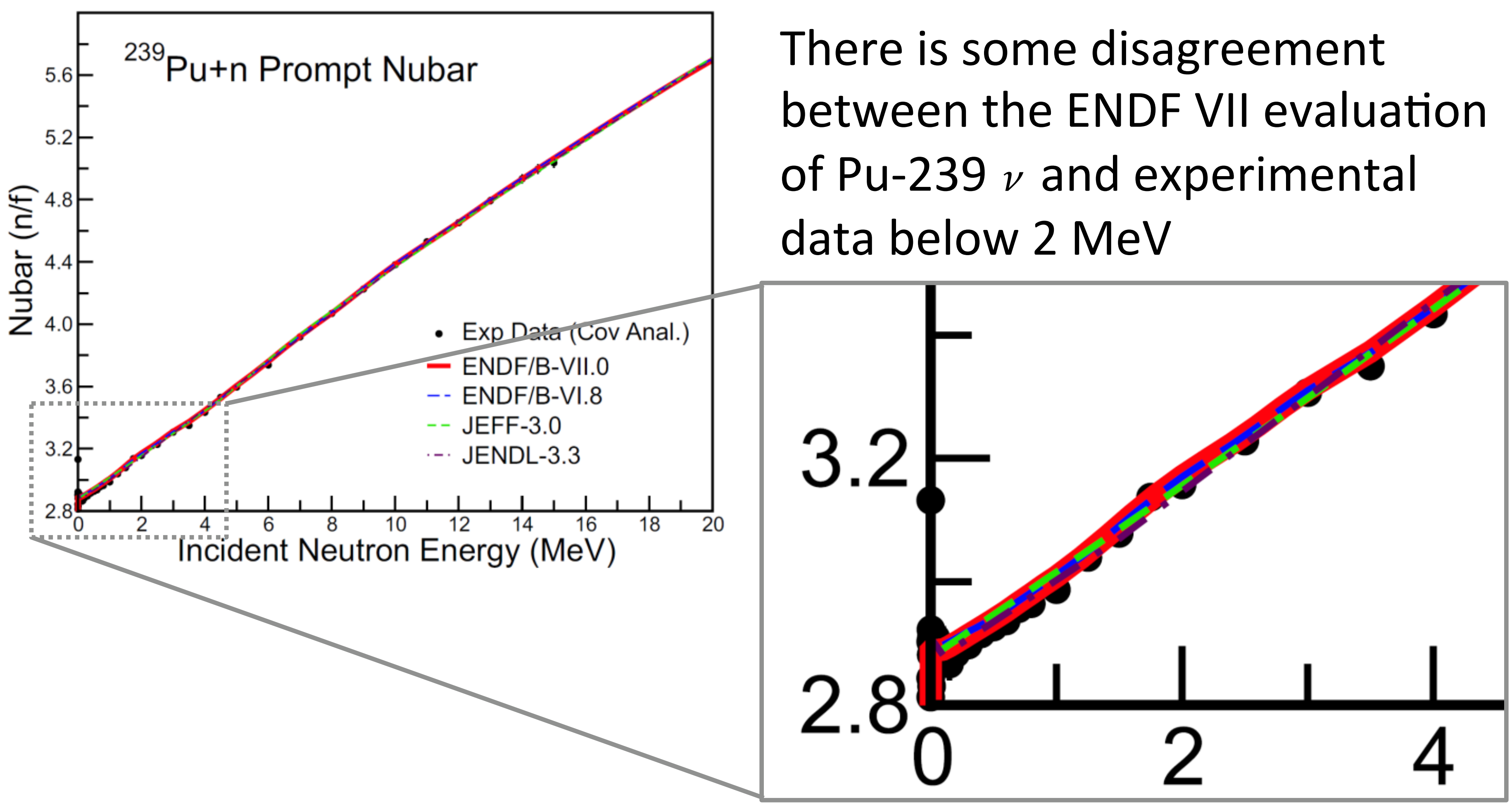


Plutonium Cross Sections

- MCNPX-PoliMi was previously tested against ESARDA benchmark measurements of MOX
- The code accurately predicted the multiplicity distribution
- However, the MOX samples used in the benchmark had extremely low multiplication



Pu-239 Induced Fission Neutron Multiplicity

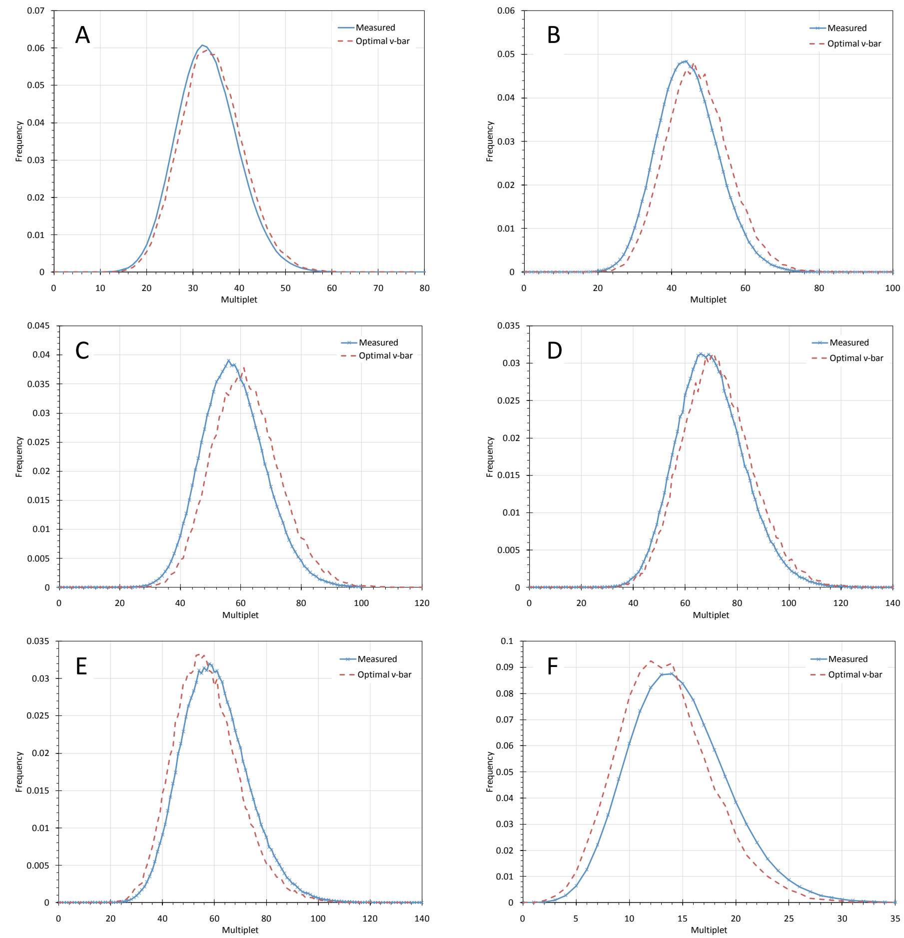


There is some disagreement between the ENDF VII evaluation of Pu-239 ν and experimental data below 2 MeV

What if the ENDF VII Pu-239 ν is incorrect?

Reflector	Deviation from Experiment			
	Mean		Variance	
	ENDF VII ν	Reduced 1.1%	ENDF VII ν	Reduced 1.1%
None	4.2%	0.3%	6.4%	-0.1%
0.5”	9.0%	3.4%	14.1%	4.4%
1.0”	12.8%	4.4%	27.8%	9.4%
1.5”	12.8%	1.3%	32.7%	3.8%
3.0”	12.9%	-5.4%	41.0%	-5.7%
6.0”	9.4%	-10.4%	26.8%	-11.6%

A reduction of only 1.1% in the ENDF VII ν dramatically reduces the error in the MCNPX-PoliMi calculations of the multiplicity distribution



Conclusions

- MCNPX-PoliMi simulations of the benchmark measurements exhibited systematic over-prediction of the neutron multiplicity distribution
- The over-prediction tended to increase with increasing multiplication
- MCNPX-PoliMi had previously been validated against only very low multiplication benchmarks
- Every potential source of the bias (that we could conceive of) was eliminated except for the Pu-239 ν
- A very small change (-1.1%) in the Pu-239 ν dramatically improved the accuracy of the MCNPX-PoliMi simulation for all 6 benchmark measurements; this change appears to be within the uncertainty of the ENDF VII evaluation
- This observation is consistent with the trend observed in the bias exhibited by the MCNPX-PoliMi simulations: a very small error in ν is "magnified" by increasing multiplication
- All the evidence points to a bias in the Pu-239 ν

Future Work

- Our analysis reduced the ENDF VII Pu-239 ν by a global factor of 1.1% for all incident neutron energies
- This adjustment was estimated by minimizing the sum of squared errors for the entire set of calculations
- In other words, we used nonlinear regression on a simple scalar correction to ν to choose the "best estimate" of the scaling factor for ν
- In fact, ν is a function of incident neutron energy, $p(\nu|E)$, though the functional form is debatable
- Regression methods could be used to estimate the parameters of a simple functional form for the correction, e.g., a linear correction in energy
- I think we should communicate our findings to the evaluation committee for Pu-239 $\nu|\mathrm{E}$
- In addition, I would like to propose incorporation of the benchmark experiments in the next evaluation of Pu-239 $\nu|\mathrm{E}$
- Data assimilation methods (see Cacuci, *NS&E* **165**, pp. 18-44, 2010) could be used to rigorously incorporate these measurements into the evaluation

Acknowledgment

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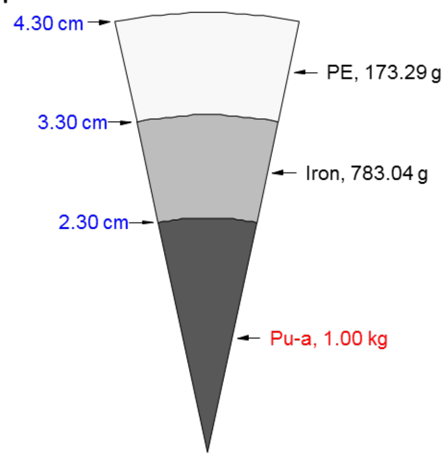
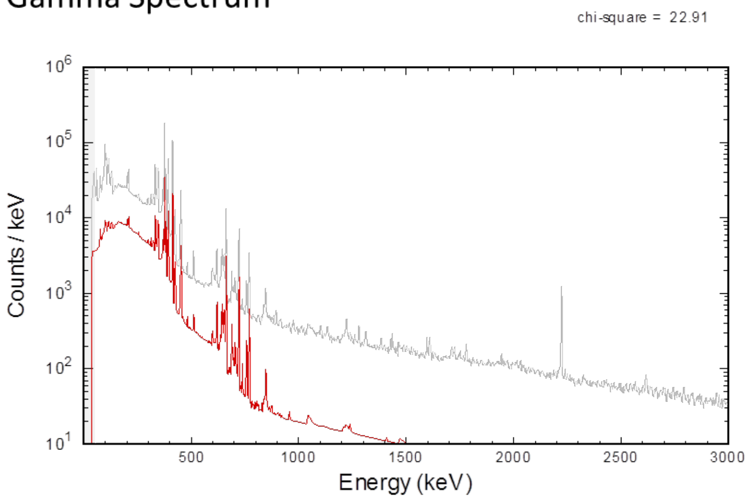
Supplemental Slides

GADRAS Inverse Solver: Initial Guess

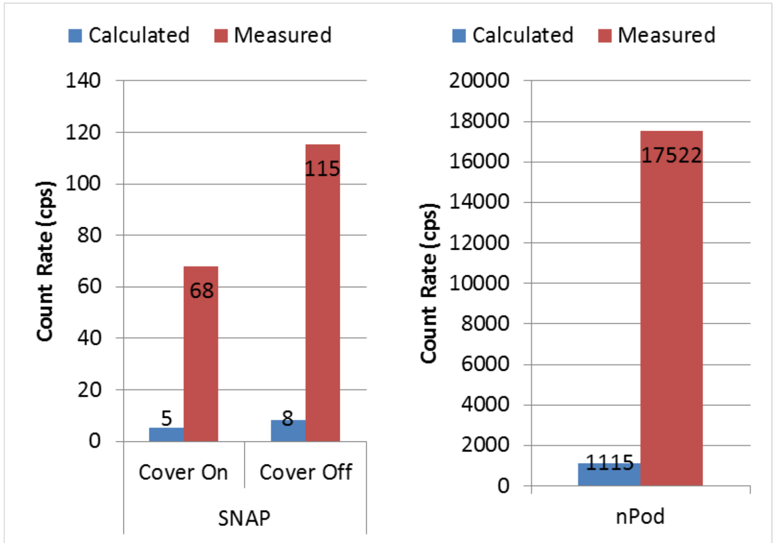
Model



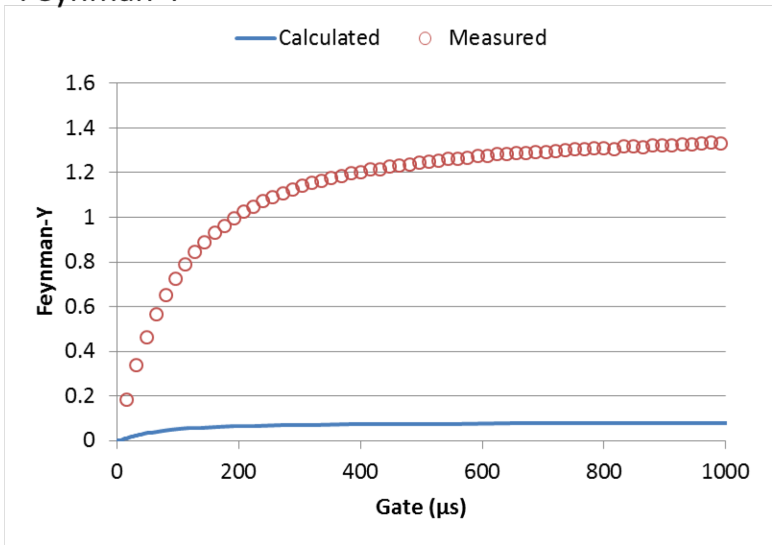
Gamma Spectrum



Neutron Count Rate

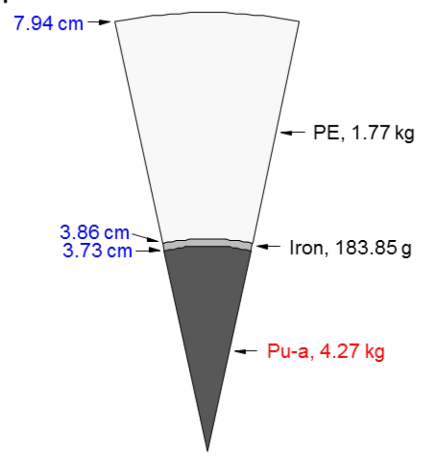


Feynman-Y

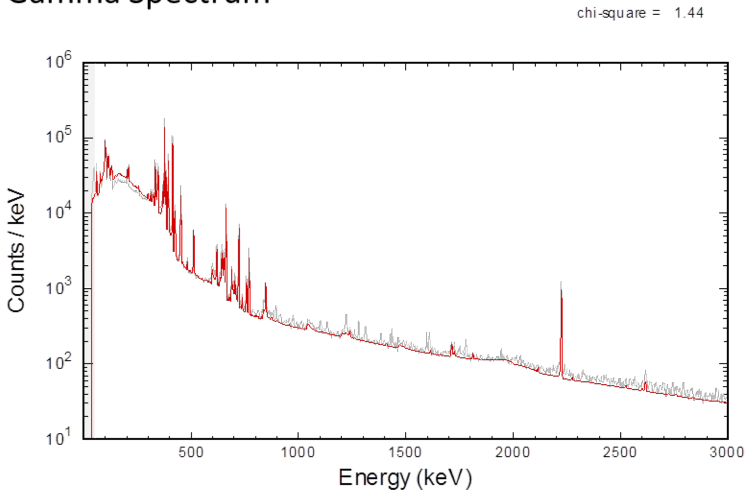


GADRAS Inverse Solver: Solution

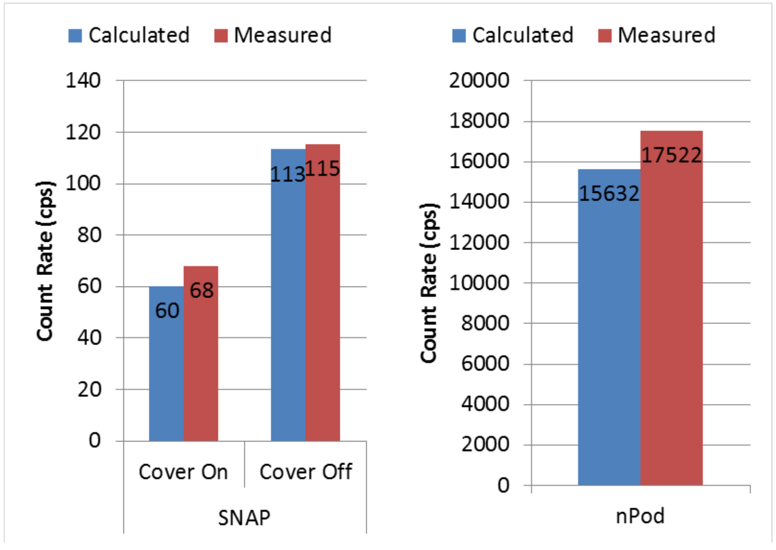
Model



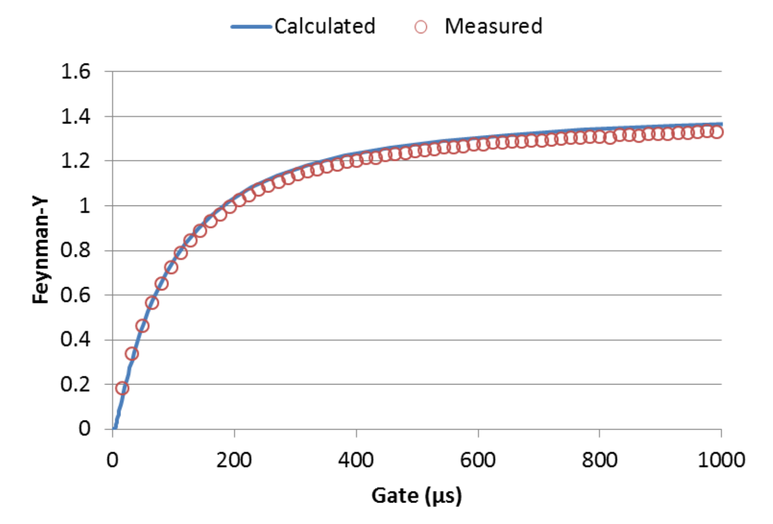
Gamma Spectrum



Neutron Count Rate



Feynman-Y



Inverse Solver Validation Test Results

Reflector	Plutonium Mass (kg)		Neutron Multiplication		Reflector Thickness (cm)	
	Estimated	Actual	Estimated	Actual [a]	Estimated	Actual
None	4.3	4.5	4.4	4.5	N/A [b]	0.0
0.5 inch	4.6		5.5	5.8	0.8	1.3
1.0 inch	4.6		7.0	7.8	1.9	2.5
1.5 inch	4.3		9.9	10.4	4.2	3.8
3.0 inch	4.4		15.3	16.3	7.9	7.6
6.0 inch	4.4		16.4	17.1	15.0	15.2

[a] The "actual" neutron multiplication was estimated using MCNP5.

[b] For the bare case, no reflector was included in the initial model.